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# An Omnidirectional FM Monitor Hydrophone for Low-Frequency Towed Projectors

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**Naval Undersea Warfare Center Division
Newport, Rhode Island**

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An omnidirectional standard hydrophone has been developed for accurately determining the sound-pressure level of an underwater, high-power, towed projector through a common multiconductor tow cable. This monitor hydrophone reduces the effect of electrical crosstalk between individual conductors over the system bandwidth of 10 Hz to 10 kHz. Preliminary measurements show reductions in crosstalk of up to 60 dB using this system.

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## 1. INTRODUCTION

When a reference hydrophone of conventional design is used to monitor the sound pressure level of a towed underwater sound projector through a common tow cable, the results are generally unsatisfactory. Unintentional coupling of the projector signal into the hydrophone conductors causes severe degradation of the hydrophone signal. This interference, called crosstalk, occurs because of capacitive and inductive coupling between the projector and sensor lines in the tow cable.

The coupled signal is, in effect, added to the monitor signal in the cable. Because the monitor signal and coupled signal are at the same frequency, the unwanted coupling often goes unnoticed, and the corrupted monitor signal is incorrectly interpreted as representing the true sound pressure level (SPL).

The crosstalk problem is aggravated by several factors. First, tow cables often do not have shielded wires available. Shielded wires are less susceptible to coupled interference, but they are not always available for use by the hydrophone. Second, tow cables are often quite long. Capacitive coupling between individual conductors in the cable increases with cable length. Third, high voltages or currents are often delivered to the projector via the tow cable, placing high-level signals close to the low-level hydrophone output signal. Coupled interference is directly proportional to the amplitude of the interfering signal. Finally, as signal frequencies increase, the degree of unwanted coupling also increases.

Before development of the H91 Monitor Hydrophone System (hereafter referred to as the "H91 system"), several unsuccessful methods were tried for dealing with crosstalk. These methods included the use of separate cables, laced together, for the hydrophone and projector signals and the use of a separate vessel to tow the monitor hydrophone. Both of these methods proved impractical. Another attempt to avoid the problem dispensed with the monitor hydrophone altogether. This method used the calibrated transmitting response curve of the projector to determine the SPL for a particular drive level. However, the curve was valid only at the temperature and pressure at which the calibration was done.

If the harmful effects of crosstalk could be defeated, the most practical monitor for an underwater projector would be a hydrophone stationed at a fixed distance from the sound source, operating through the same tow cable. The H91 system has been developed at the Naval Undersea Warfare Center, Underwater Sound Reference Detachment (USRD), Orlando, FL, specifically to overcome the problem of crosstalk in a multiconductor tow cable. The H91 system, therefore, provides an accurate measurement of projector SPL while using a single tow cable for both projector and hydrophone.

The H91 system solves the crosstalk problem by using frequency modulation (FM) for the hydrophone signal. This method, widely used for radio communications today, carries the information in the hydrophone signal as frequency variations rather than amplitude variations.

Crosstalk primarily corrupts signal amplitude, but it has little effect on its frequency. The H91 receiver reconverts (demodulates) the FM hydrophone signal to ordinary audio with excellent fidelity even in the presence of strong crosstalk.

The H91 system has been available as a USRD standard for about 10 years. Over time, USRD has made improvements to enhance system performance and reliability. Currently, the H91 system electronics are being updated. The new version will be called H91D to distinguish it from earlier versions. This report discusses the overall design of the H91 system and details the H91D electronics. The H91D will become the off-the-shelf version of the H91 system.

Figure 1 is a diagram of a towed projector using the H91 system. The H91 sensor converts acoustic energy in the water into an electrical signal, which is then passed to the preamplifier where it is conditioned and converted to an FM signal. The FM signal is passed up the tow cable on a spare wire pair to the receiver on the ship. Along the way, the FM signal becomes contaminated by audio crosstalk. Filtering and limiting at the front end of the receiver remove this crosstalk. The signal is then demodulated, and the output is made available at a front-panel connector.

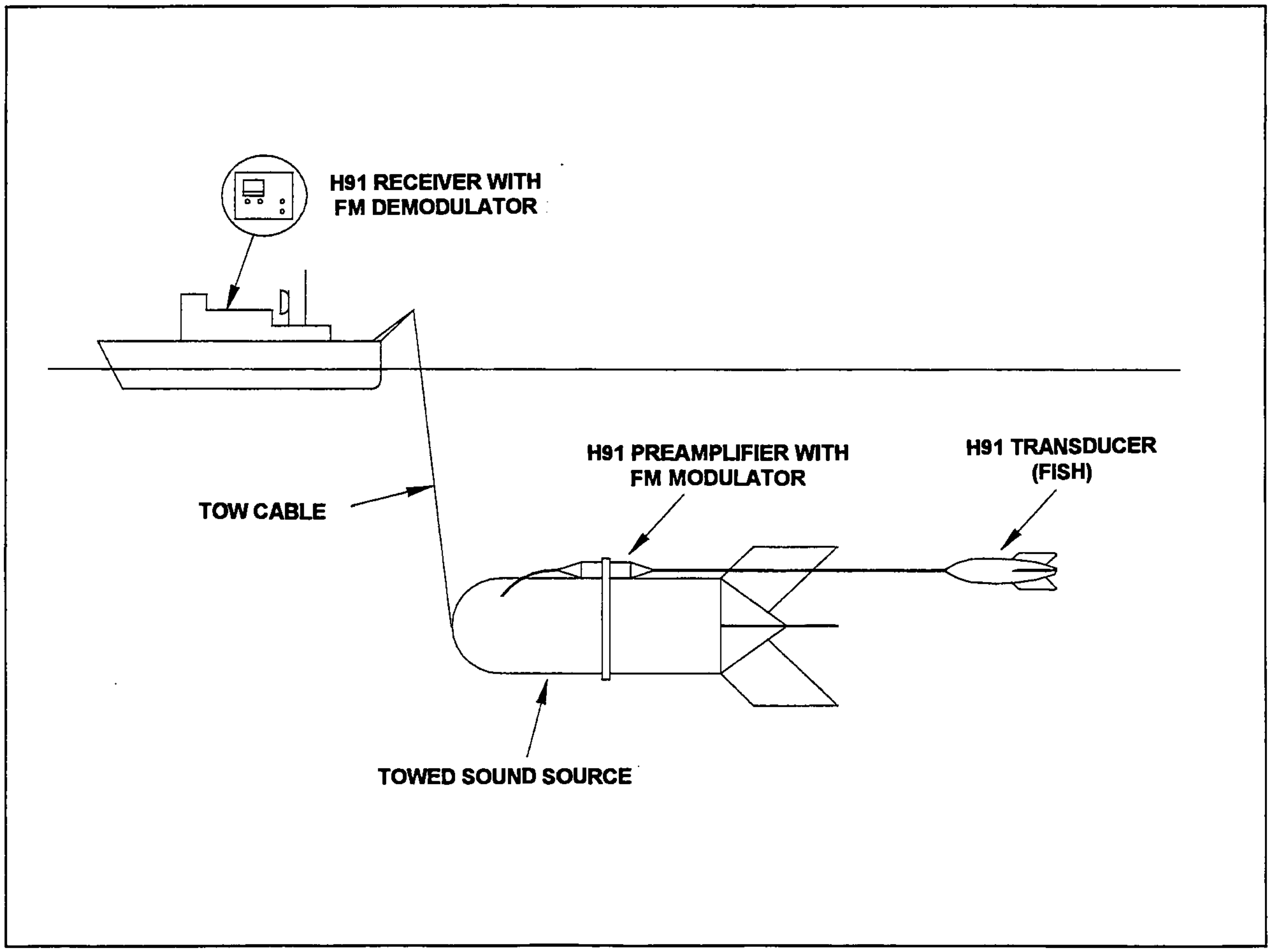


*Figure 1. Diagram of H91 Monitor Hydrophone System in Use at Sea*

## 2. SYSTEM DESCRIPTION

The USRD H91 system is used to measure remote sound pressure fields of high acoustic intensity in the 10-Hz to 10-kHz frequency range. The system employs a hydrophone positioned a fixed distance from the projector. Both projector and hydrophone share the same tow cable. For a fixed gain, the system requires only a single wire pair or coaxial cable within the overall tow cable. If remote selection of the three built-in gains is desired, a third conductor is required in the tow cable. The system can accommodate long tow cables, provided the hydrophone wire pair is not highly lossy or resistive. The appendix gives complete specifications for the H91 system.

Figure 2 is a photograph of the H91 system. The system consists of three parts: (1) hydrophone sensor assembly (sometimes called the fish), (2) preamplifier assembly, and (3) shipboard receiver. A block diagram of the system is shown in figure 3.

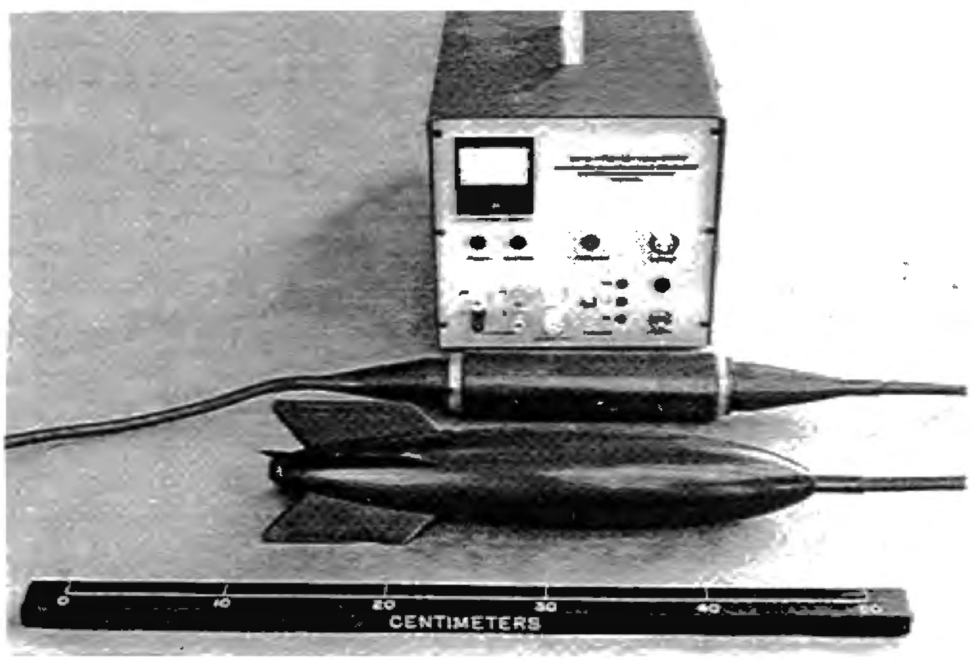


*Figure 2. H91 Monitor Hydrophone System*

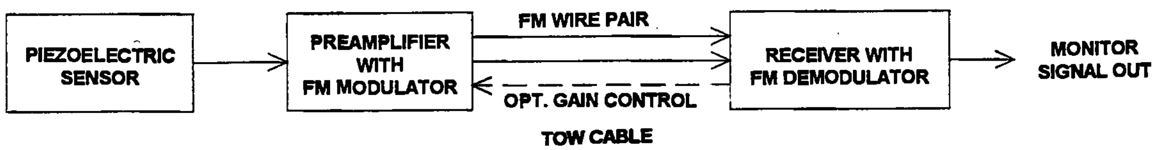


*Figure 3. Block Diagram of the H91 System*

The H91 hydrophone is a piezoelectric ceramic sensor potted in a hydrodynamically shaped polyurethane casing and towed behind the source projector. A shielded hydrophone cable (typically 3 m long) connects the hydrophone to the H91 preamplifier assembly. The preamplifier contains circuitry that conditions the hydrophone output signal and changes it to FM. Power for the preamplifier is supplied by the shipboard H91 receiver. This receiver filters and demodulates the FM signal from the H91 preamplifier. The system operates on a wire pair in the tow cable.

The preamplifier has three built-in gains available: -20 dB, 0 dB, and +20 dB. The sensor nominal free-field voltage sensitivity (FFVS) is -201 dB re 1 V/$\mu$Pa. The SPL range handled by the H91 system is shown in table 1.

*Table 1. H91 SPL Range vs Preamplifier Gain*

| Preamplifier Gain (dB) | FFVS (dB re 1 V/$\mu$Pa) | SPL Range (dB re 1 $\mu$Pa) | Output Level at Receiver (dB V) |
|---|---|---|---|
| +20 | -181 | +127 to +187 | -54 to +6 |
| 0 | -201 | +167 to +207 | -34 to +6 |
| -20 | -221 | +187 to +227 | -34 to +6 |

The three preamplifier gains shown in table 1 can be selected remotely at the receiver if a third conductor is available in the tow cable. Otherwise, the user specifies which gain is required for the application, and that gain is fixed in the delivered system.

Each H91 system, (hydrophone, preamplifier, and receiver) is calibrated as a unit at the USRD. Interchanging H91 system components is not recommended because doing so could affect system calibration.

## 2.1 HYDROPHONE ASSEMBLY

The hydrophone assembly, or fish, is designed to be towed a fixed distance behind the projector. This arrangement decouples the fish from the projector structure and places it in the farfield[1] for most projectors. The streamlined shape of the hydrophone assembly gives it hydrodynamic stability and mechanical isolation from the projector. The sensor has an omnidirectional directivity pattern in all planes. Figure 4 shows the components of the assembly (not drawn to scale).

The omnidirectional sensor element is centered on the X-axis (pitch) and Y-axis (heading) of the assembly and is placed 16.6 cm from the cable/potting interface on the Z-axis. Figure 5 is a photograph of the encapsulated sensor.

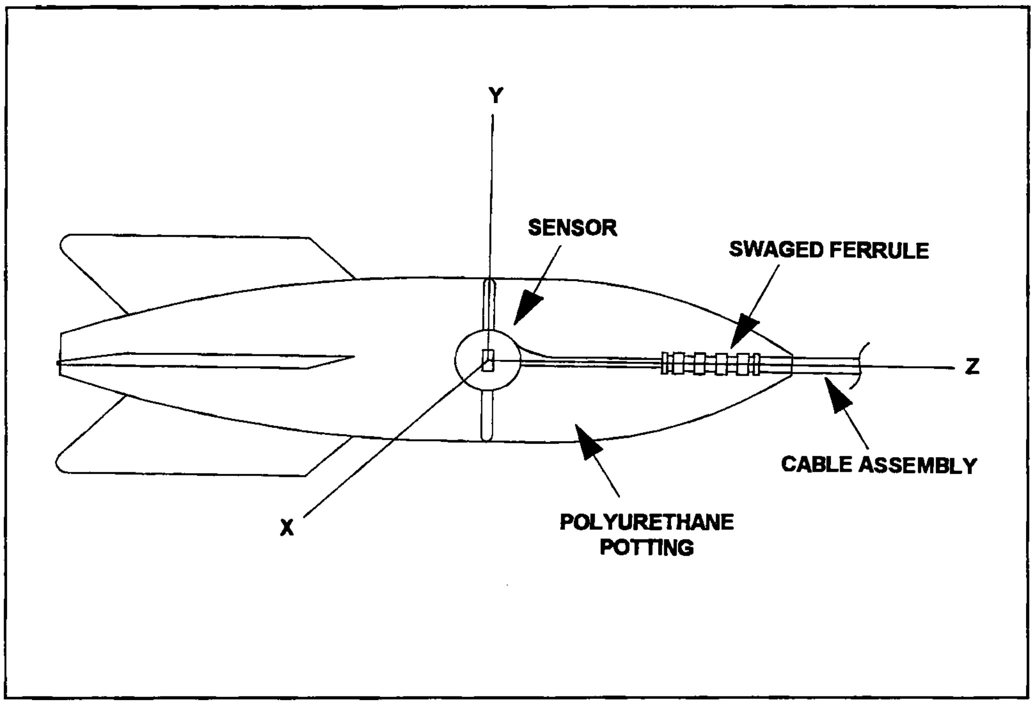


*Figure 4. Sketch of Hydrophone Assembly or Fish*

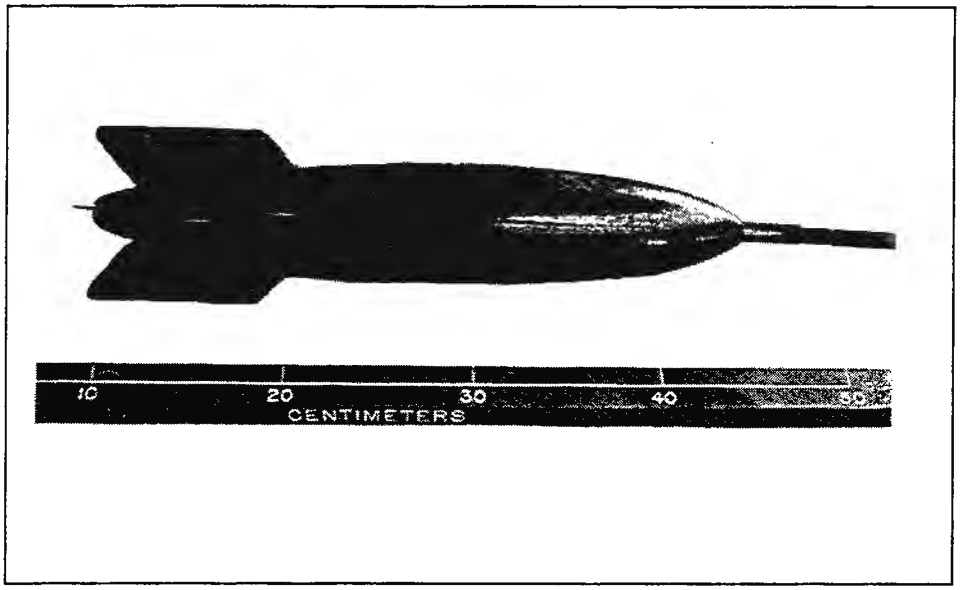


*Figure 5. Hydrophone Assembly*

Type C0-03MOF cable (MIL-C-3432) serves as both the electrical and mechanical connection between the fish and preamplifier assembly. This cable type has an internal coaxial cable member that carries the sensor signal to the preamplifier. An outer metal braid serves as an electrostatic shield and strength member for the cable under tow. The cable connects to the fish through a swaged copper ferrule. Potting compound encapsulates the cable and fish assembly.

### *2.1.1 Hydrophone Sensor Element*

Design of the piezoelectric element used as the H91 sensor was influenced by many factors, including a requirement for ruggedness and stability. An omnidirectional directivity pattern was required over a 10-kHz system bandwidth with a resonant frequency well above 10 kHz. Sensitivity had to be tailored for the majority of towed source applications. A hollow sphere of lead zirconate titanate (PZT) was selected for the sensor material. Sphere dimensions of 1-inch outer diameter and 0.125-inch thickness (2.54 cm and 0.32 cm, respectively) were chosen for this design.

### *2.1.2 Hydrophone Body*

Because of its hydrodynamic shape, the fish generates negligible flow noise under tow, resulting in a good acoustic signal-to-noise ratio. The internal copper cable ferrule and polyurethane sensor mounts cause minimal acoustic reflections so that signals arriving at the sensor are relatively free of interference.

The encapsulant material used is PRC 1538 black polyurethane. The impedance of this material provides an excellent coupling medium for the sensor. At low frequencies, the characteristic impedance ($\rho c$, the product of material density and sound speed) of the encapsulant is near that of water, making it acoustically near-transparent.[2] The encapsulant is tough and under normal conditions will not break, tear, or stretch. It provides excellent abrasive protection.

## 2.2 PREAMPLIFIER ASSEMBLY

The H91 preamplifier circuitry conditions the sensor output and converts it to an FM signal. The preamplifier is contained in a corrosion-resistant, stainless steel pressure housing, as shown in figure 6.

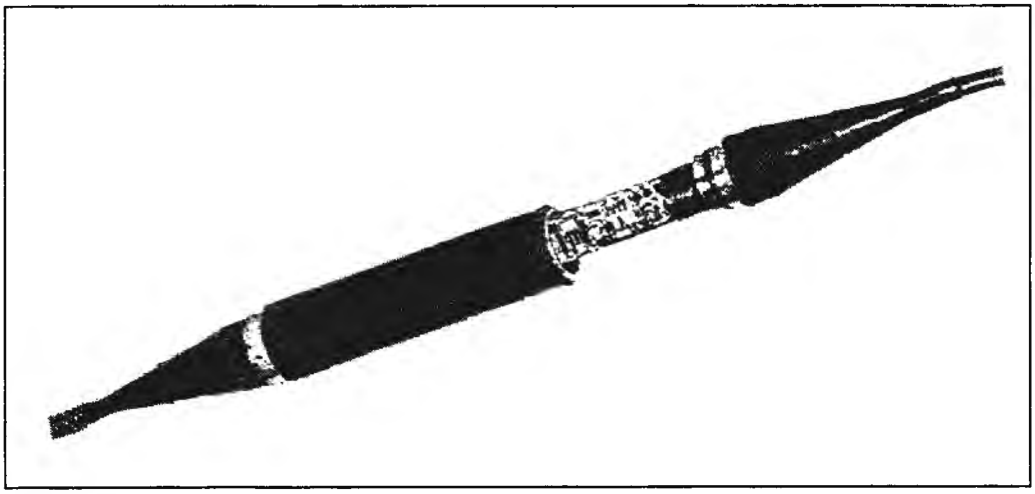

*Figure 6. H91 Preamplifier Assembly Housing (Opened to Show Preamplifier)*

The preamplifier housing is a sealed unit with cable glands (rubber-molded connectors) attached to both ends. It is designed to withstand pressures up to 3300 psi, corresponding to a 2200-m depth. The tow cable connects the preamplifier output to the shipboard receiver.

The preamplifier (1) buffers the high-impedance signal from the sensor and provides optional amplification or attenuation, (2) modulates the buffered signal, and (3) provides drive capability for long tow cables; it is electronically protected against overloads caused by high SPL. The output wire pair used for signal output also provides dc power to the preamplifier. This single output wire pair is sufficient for preamplifier operation.

### 2.3 SHIPBOARD RECEIVER

The H91 receiver, normally placed in the ship's electronics laboratory, interfaces to the H91 preamplifier through the tow cable. The receiver conditions and demodulates the preamplifier FM signal while rejecting unwanted crosstalk signals on the cable. The receiver also provides dc power to the preamplifier and, optionally, controls its gain. Figure 7 is a photograph of the H91B receiver. The H91D receiver will be similar.

*Figure 7. H91B Receiver Front Panel*

The main power on/off switch for the H91 system, signal output connector, dc supply current meter, a three-way gain switch, and several system status lamps are located on the exterior of the receiver. Calibration signal connectors are also provided for special benchtop testing.

In the receiver circuitry, the low-level FM signal from the preamplifier is filtered to remove unwanted crosstalk and amplified to compensate for cable loss. The signal is then limited (clipped) and applied to a phase-locked loop demodulator. The demodulated signal is filtered, amplified, and made available at a front-panel connector. Status lamps on the front panel indicate (1) when the system is powered and locked onto the FM carrier, (2) if the FM signal is excessive, and (3) whether the hydrophone wire pair is open or shorted.

## 3. CONSTRUCTION

### 3.1 HYDROPHONE SENSOR ELEMENT ASSEMBLY

The sensor element (shown in figure 8, but not drawn to scale) consists of two Navy Type I[3] PZT hemispheres joined with epoxy to form a spherical element. The inner electrodes, i.e., the inner surfaces of the two hemispheres, are connected in parallel to form the sensor high side. Similarly, the outer electrodes are connected in parallel to form the sensor low side. The inner electrode wire is brought out through a small hole drilled through the apex of one hemisphere. Epoxy at the site of this hole provides a hermetic seal.

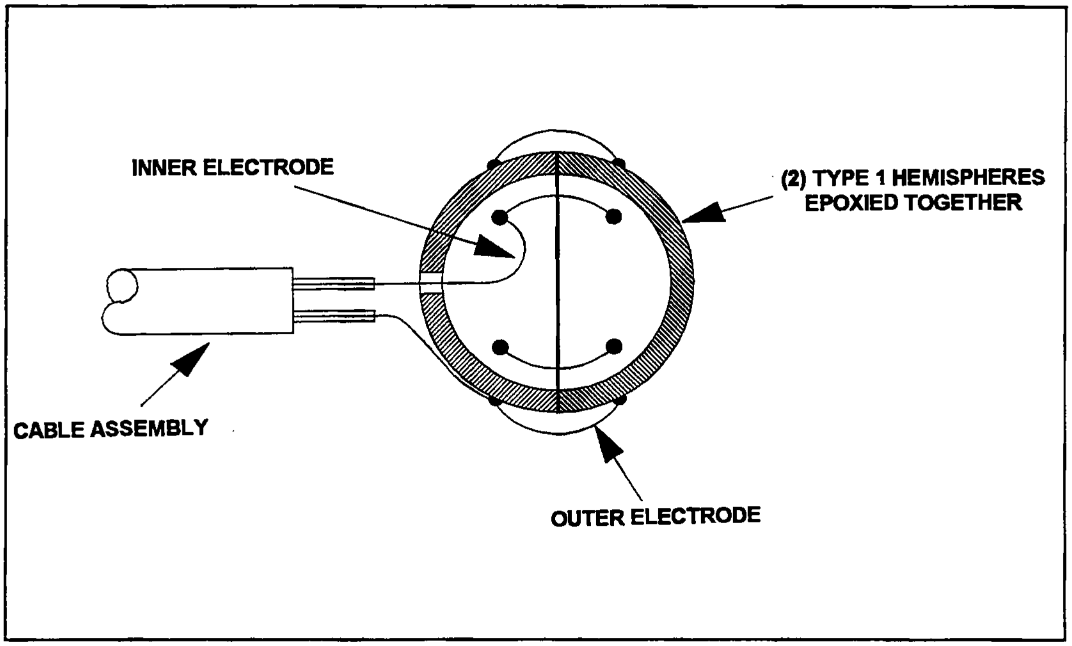


*Figure 8. Detail of Spherical Sensor*

### 3.2 HYDROPHONE BODY ASSEMBLY

Construction of the hydrophone assembly entails preparation of the electrical cable, electrical connection of the sensor to the cable, priming of the cable and sensor in preparation for potting, mounting of the assembly in the potting mold, and potting of the assembly.

The cable is prepared by trimming insulation from the leads. The bare leads of the coaxial cable are then soldered to the sensor. For correct polarity, the inner electrode wire is soldered to the coaxial center conductor and the outside electrode wire is connected to the coaxial shield. Type C0-03MOF cable[4] is used because of its relative strength. The sensor is attached to the cable using cured sections of PRC 1538® polyurethane as supports. Type PR 420® primer is used to prime metal parts, and the rubber cable jacket is primed with PR 1523®.

The cable and sensor assembly are then mounted in the potting mold (figure 9) and centered. The sensor is aligned with an "acoustic center mark" on the mold. Small standoff blocks of cured PRC 1538® polyurethane are attached to the sensor and cable to maintain sensor and cable positions while the potting material vulcanizes.

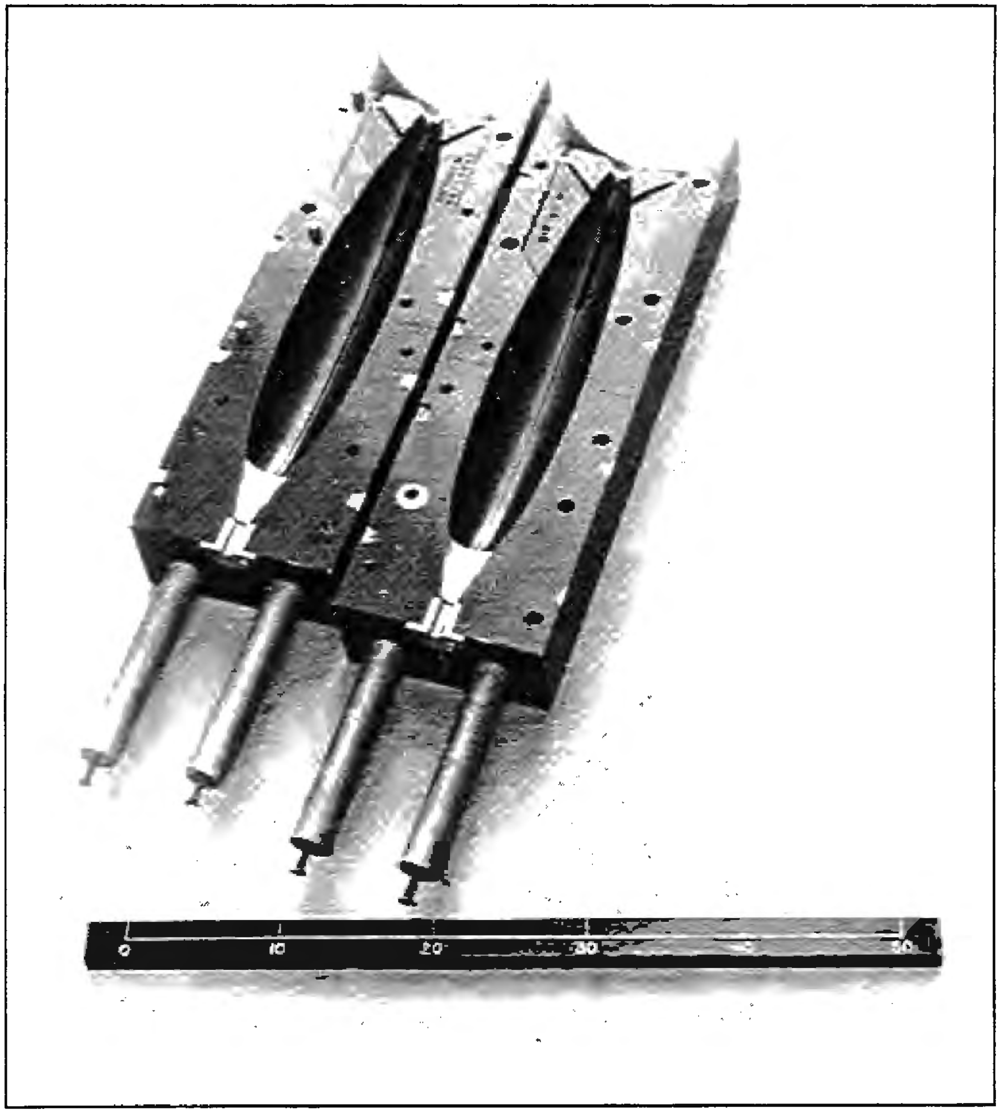

*Figure 9. H91 Hydrophone Potting Mold*

The mold and the polyurethane mixture is preheated to 85°C and is then slowly poured into the mold until the mold is full. The mold is inclined at 18° to allow air bubbles to escape. The polyurethane is then cured at 85°C for approximately 15 hours. Finally, the mold is separated into four sections to permit removal of the finished assembly.

## 3.3 PREAMPLIFIER AND HOUSING

The preamplifier housing material is type 316 stainless steel and is designed to withstand hydrostatic pressures higher than system requirements. The metal housing provides an electrostatic shield for the preamplifier circuitry. The housing is rugged and highly resistant to saltwater corrosion. The outer surface is covered with a butyl rubber sleeve that provides both a good mounting surface and decoupling from projector vibrations. O-rings are mounted on each connector to seal the housing against water intrusion, while permitting easy removal of the preamplifier for maintenance. The preamplifier is held in position by connector jacks mounted on each end of the printed circuit board.

## 3.4 CABLE ASSEMBLY

A USRD-designed type C0-03M0F cable is used to connect the preamplifier to both the sensor and the tow cable. A 3-m-long cable connects the sensor to the preamplifier input, and a 1-m-long cable connects the preamplifier output to the tow cable. Figure 10 shows the cabling to the preamplifier (not drawn to scale).

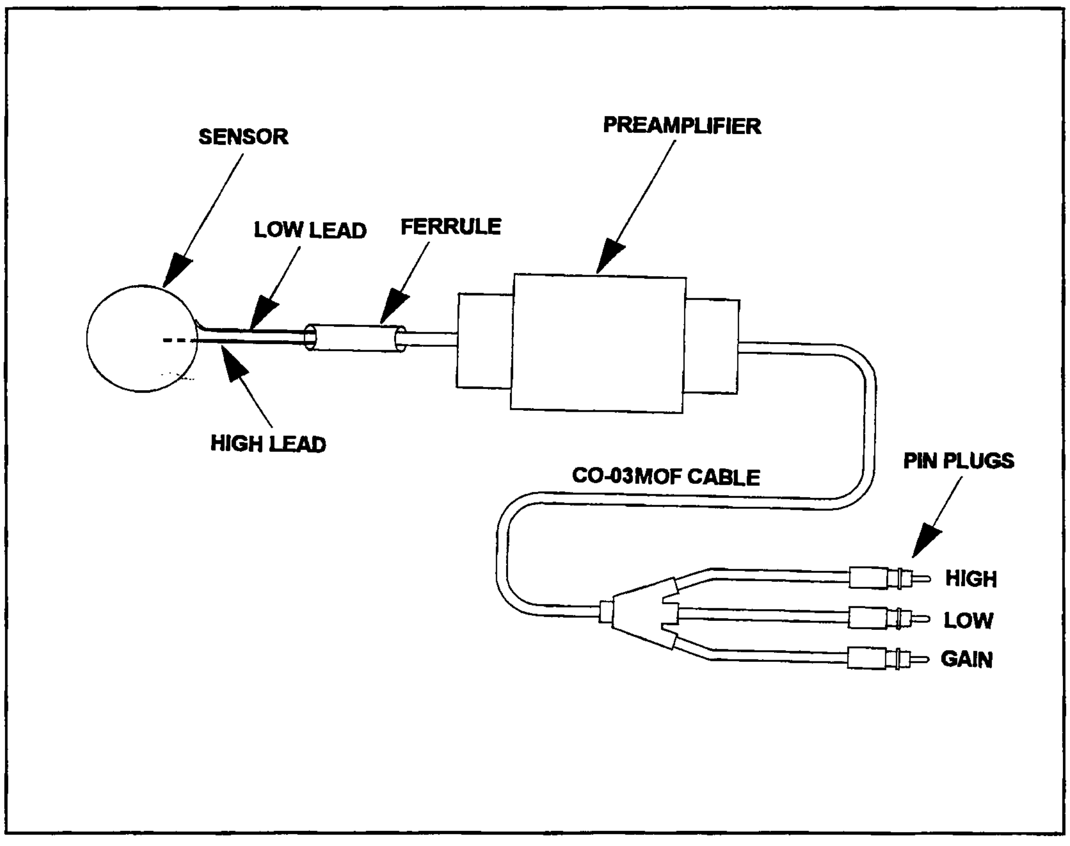


*Figure 10. Cable Assembly Diagram*

The cable assembly provides both mechanical and electrical connections to the preamplifier. The low-capacitance, coaxial cable member is used to conduct the signal in both the input and output cables. Also, a conductor in the output cable is used as the gain control line. The output cable connects to the tow cable using single-pin, male underwater connectors. For mechanical strength, a copper ferrule is swaged near each end of the cables prior to encapsulation.

## 3.5 SHIPBOARD RECEIVER

The H91 shipboard receiver is housed in a commercial benchtop instrumentation box. Figure 11 shows the H91B receiver; the H91D receiver will be similar. The box and front panel are modified by the USRD for the H91 application. Connectors, gain switch, and status lamps are mounted on the front panel. Inside the box, the receiver circuitry is on two printed circuit boards. Board A1 is a four-layer printed circuit board containing the receiver current source, amplifiers, filters, and demodulator. Board A2 is a two-layer printed circuit board containing commercial power supply modules that power both the receiver and the preamplifier.

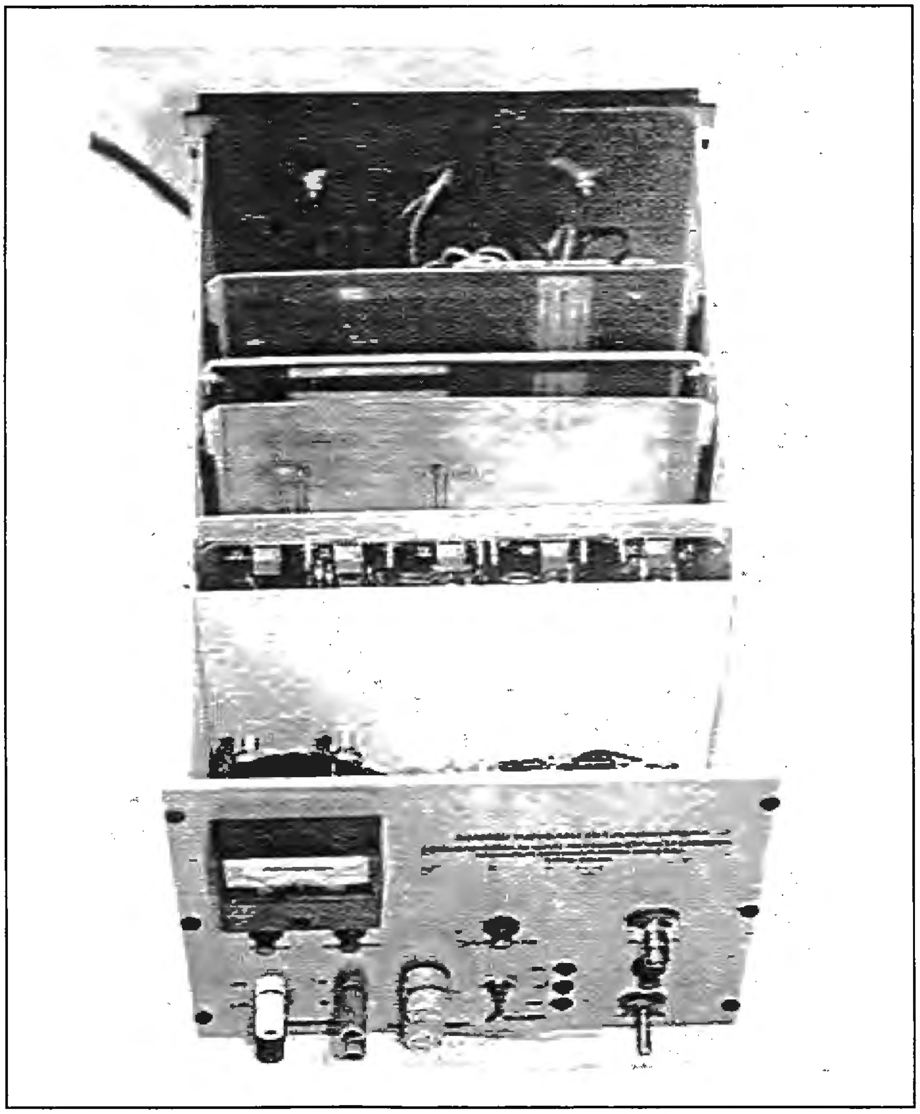

*Figure 11. H91B Receiver Interior*

# 4. SYSTEM TECHNICAL DISCUSSION

## 4.1 SENSOR ELEMENT

A Navy Type I, piezoceramic hollow sphere was chosen as the sensor element for the H91 monitor hydrophone because its geometry exhibits a flat frequency response, is omnidirectional, and has good sensitivity over the required bandwidth. The sensitivity is stable within 2 dB to a depth of 152 m.

Even though the theory and analysis of a spherical acoustic sensor have been well documented in previous USRD reports,[5-11] several important topics are reviewed in this section. The important parameters that determine the overall operational response of a spherical hydrophone sensor are

- FFVS,
- diffraction,
- resonance frequency,
- capacitance,
- low-frequency cutoff, and
- static pressure and temperature capability.

### *4.1.1 Free-Field Voltage Sensitivity*

The operational frequency range of the H91 system is 10 Hz to 10 kHz, which is within the flat region of the FFVS response curve of the spherical sensor (figure 12). The sensor is sensitive to frequencies exceeding 100 kHz, but the H91 electronics limit the system response to 10 kHz.

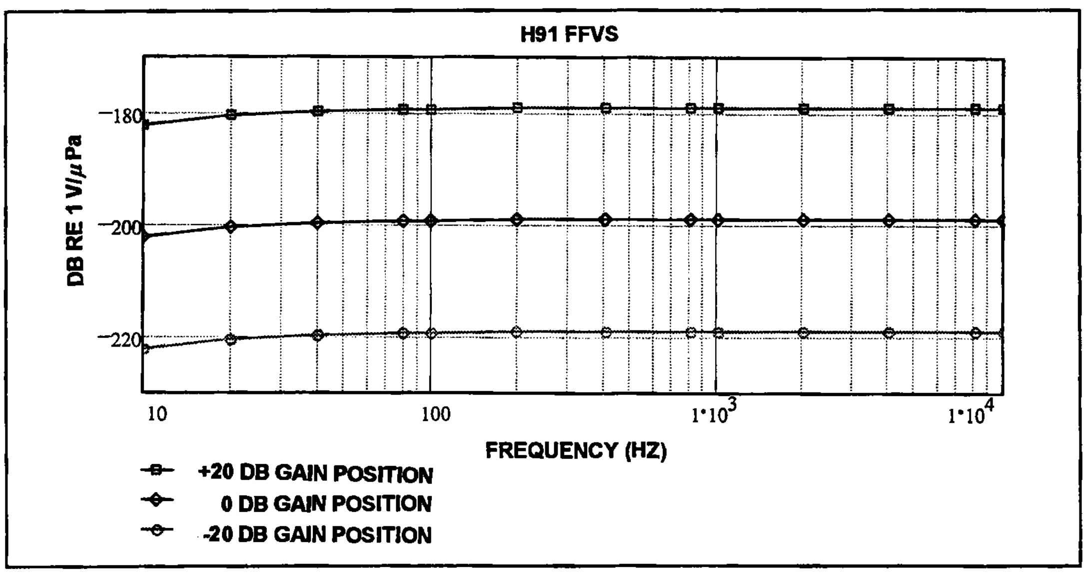


*Figure 12. H91 Typical FFVS*

Theoretical calculation of the static sensitivity for the spherical sensor yields a value of -199.2 dB re 1 V/μPa. This result is valid at frequencies above the low-frequency cutoff and below resonance. For the H91 system, this bandwidth overlaps the desired 10 Hz-10 kHz operational range. Details on developing an equivalent circuit model for a thin-walled sphere are given by Timms et al.[9]

### *4.1.2 Resonance Frequency*

The resonance frequency of a thin-walled sphere greatly influences its overall frequency response. The resonance frequency is inversely proportional to the size of the sphere. The sphere must be small enough to place its resonance frequency well above the operational bandwidth. The theoretical resonance frequency for the H91 sensor was calculated to be 79.8 kHz using the technique of Jenne and Ivey.[7] That frequency is well above the 10-kHz bandwidth of the H91 system.

### *4.1.3 Diffraction*

At high frequencies, where the dimensions of the sensor are no longer small compared with a wavelength, a phenomenon called diffraction occurs.[10] Diffraction causes a rolloff in the sensor FFVS between the flat portion of the curve and the resonance peak. The magnitude of the diffraction effect depends on the size and shape of the hydrophone sensor and varies with the acoustic sound field. The computed diffraction for the sensor type used in the H91 is given by Ivey[5] and Henriquez.[10] This effect occurs well above the 10-kHz bandwidth of the H91 system.

### *4.1.4 Low-Frequency Cutoff*

Low-frequency cutoff is the frequency at which the sensor FFVS has fallen 3 dB below the flat portion of its curve. Below the low-frequency cutoff, the response falls at a rate of 6 dB per octave.[5, 6] The sensor low-frequency cutoff is a function of its blocked capacitance and resistance together with preamplifier input impedance. For the H91 sensor, this value is below 1 Hz.

### *4.1.5 Capacitance*

Sensor capacitance is a very important electrical property to consider when designing a piezoceramic sensor. Capacitance is closely linked with other design parameters in meeting key system requirements. If sensor capacitance is too low, a significant fraction of its output voltage can be lost because of loading by the cable and preamplifier. This voltage loss can be overcome somewhat by increasing preamplifier input impedance. However, this procedure often leads to other problems such as unwanted noise and coupled interference.

Tims et al.[9] By using the dimensions of the H91 sensor, a nominal capacitance value of 5000 pF can be predicted.

The equivalent noise pressure of a hydrophone system is dependent on the capacitance of the hydrophone sensor. Equivalent noise pressure decreases with increasing sensor capacitance because sensor impedance decreases with increasing capacitance. Because the noise sources in the front-end of the preamplifier work into this impedance, their effect is reduced if the impedance is lowered. An excellent discussion of hydrophone noise is given by Tims.[12] Because the SPL field monitored by the H91 is typically very strong, noise is generally not an important issue.

### *4.1.6 Static Pressure and Temperature Capability*

For the H91 sensor, sensitivity of FFVS to static pressure changes is negligible at typical towing depths. The hollow ceramic sphere can be subjected to a change in static pressure of 0 to 10,000 psi with a change in FFVS of less than 3 dB. A detailed discussion of the theory of FFVS sensitivity to static pressure is discussed by Jenne and Ivey.[7]

The H91 sensor also exhibits negligible change in sensitivity over a temperature range of 0 to 30°C.[6]

## 4.2 PREAMPLIFIER AND RECEIVER

### *4.2.1 Hydrophone Preamplifier Design*

Figure 13 is a block diagram of the H91 hydrophone preamplifier, which is the interface between the acoustic sensor and the shipboard receiver. In figure 13, the sensor input is at the left and the tow cable is at the right.

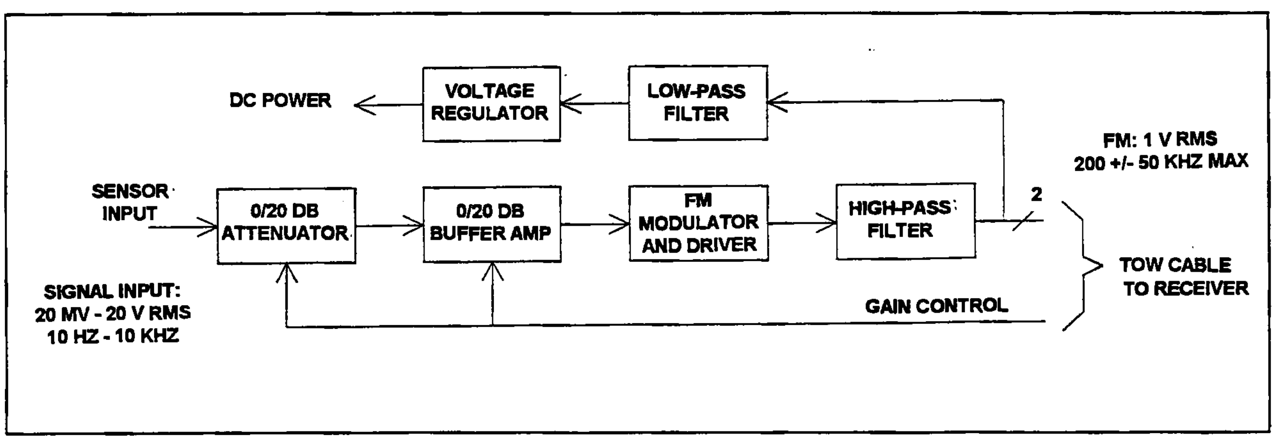


*Figure 13. H91 Preamplifier Block Diagram*

The low-level signal from the sensor is brought to the preamplifier on the coaxial member in the C0-03MOF cable. The preamplifier buffers this signal and provides optional 20-dB gain or attenuation, as explained below. A modulator then converts the signal from a varying voltage to a varying frequency. This FM signal is then amplified, filtered, and sent up to the receiver. The preamplifier FM output uses a spare wire pair or coaxial cable within the tow cable. The preamplifier dc power is supplied by the receiver on the same wire pair.

Because of the long cable lengths sometimes encountered in H91 applications, dc power is supplied to the H91 preamplifier by means of a constant current rather than by a constant voltage. A regulated 30-mA supply current is developed in the receiver and sent down the wire pair that carries the FM signal.

The high-pass filter shown in figure 13 prevents audio crosstalk on the cable from affecting the FM output stage. Similarly, the low-pass filter excludes crosstalk from the voltage regulator stage. These filters also separate the dc input and FM output signals. The subject of crosstalk is covered in section 4.3.

#### *4.2.2 Preamplifier Gain Control*

Preamplifier gain can be fixed, via jumpers, at either +20, 0, or -20 dB. Table 1 shows the ranges of SPL, end-of-cable FFVS, and output level available with these preamplifier gains. For fixed gain operation, only the single wire pair in the tow cable is required. If a third conductor is available, however, that conductor can be used as a gain control line, and each of the three gains can then be selected remotely at the receiver. A rotary switch on the receiver places +12, 0, or -12 Vdc on the gain control line to select a preamplifier gain of +20, 0, or -20 dB, respectively. (Other customized preamplifier gains are available.)

#### *4.2.3 FM Signal Bandwidth*

The output from the preamplifier FM modulator is a 1-Vrms, 200-kHz triangle wave called the carrier. The FM modulator changes (deviates) the carrier frequency in response to an input signal. If no input signal is present, the modulator output is simply the 200-kHz triangle wave. However, when a full-scale 2-Vrms signal is applied to the modulator, the carrier frequency is deviated by ±50 kHz. Inputs between these two extremes cause proportionally less deviation of the carrier. Note that the rate at which this carrier deviation takes place is equal to the frequency of the acoustic signal.

When modulated, the FM output signal becomes a very complex waveform. This complex signal must be analyzed in the frequency domain to determine its bandwidth. When this analysis is done,[13] one finds that the FM signal consists of many pairs of sidebands positioned symmetrically about the 200-kHz center frequency. In theory, there are an infinite number of these sideband pairs. However, the magnitudes of the higher order sidebands are negligibly small, and the effective bandwidth of the FM signal is finite.

To estimate the bandwidth of the FM signal, one must decide which sidebands are important and which are negligible. A commonly used guideline, known as Carson's Rule,[13] states that the significant sidebands lie within a bandwidth of

$$fc \pm (fm + fd), \tag{1}$$

where $fc$ is the 200-kHz carrier frequency, $fm$ is the modulation rate, and $fd$ is the deviation frequency. The sidebands neglected by Carson's Rule account for less than 1 percent of the FM signal power.

As stated earlier, $fm$ is equal to the acoustic signal frequency (10 Hz to 10 kHz), and $fd$ is 0 to 50 kHz. From equation (1) the maximum FM bandwidth occurs for $fm$ = 10 kHz and $fd$ = 50 kHz; that is, when the preamplifier modulator input signal is at maximum frequency and amplitude. For this case, the FM bandwidth lies (approximately) within

$$200 \pm (10 + 50)\ \text{kHz}. \tag{2}$$

Restated, the maximum FM bandwidth, $BW_{max}$, extends from about 140 kHz to 260 kHz, a total range of 120 kHz; that is,

$$BW_{max} \approx 2(fm_{max} + fd_{max}). \tag{3}$$

The hydrophone wire pair within the tow cable must be capable of carrying signals of 140 to 260 kHz with minimal cable loss. Because these frequencies are high, a coaxial cable is recommended for the FM wire pair.

### *4.2.4 Self-Noise*

All electronic systems are subject to unwanted noise. In the H91 system, noise signals are generated internally by the motion of electrons in the preamplifier and receiver circuitry. This self-noise tends to be broadband and low level.

The H91 system is also subject to strong interfering signals in the tow cable. These signals are coupled into the hydrophone wire pair resulting in the phenomenon called crosstalk. The strongest interfering signal is typically the drive voltage to the projector. The subject of crosstalk is covered in section 4.3. The present discussion deals only with self-noise.

The signal-to-noise ratio in an FM system is dependent on the level of the carrier, the level of the noise, and the modulation index $\beta$.[13] $\beta$ is simply the ratio of $fd$ to $fm$ shown as

$$\beta = fd/fm. \tag{4}$$

Acoustic signal frequency $fm$ varies from 10 Hz to 10 kHz in the H91 system. Modulator output frequency $fd$ varies from 0 to ±50 kHz as the modulator input goes from no signal to a full 2 Vrms. Therefore, the value for $\beta$ can be as large as 5000 or as low as 0 in the H91 system.

Assuming that the level of the carrier at the receiver is high compared with the noise (the usual case), it can be shown[13] that the signal-to-noise ratio at the receiver output is proportional to $\beta^2$. This relationship means that the best quality audio output from the receiver will be obtained for the highest values of $\beta$. Because *fm* is the acoustic signal frequency and *fd* is proportional to SPL, large moderate-frequency acoustic signals are processed more cleanly in the H91 system than are small high-frequency signals.

In the unusual case where the carrier level at the receiver is not high compared with the system noise, the signal-to-noise ratio at the receiver output decreases. This decrease is the result of information in the FM signal being conveyed by the frequency of the carrier, i.e., the number of zero crossings per unit time. In the limit, if noise swamps the carrier, the carrier frequency can become indeterminate. To maximize the carrier level at the receiver, low-loss cable should be used for the FM wire pair. The H91 specification (see the appendix) requires that the attenuation of the FM wire pair not exceed 30 dB at 300 kHz.

It must be stressed that the H91 system is not intended for ambient noise measurements where signal levels are small. (The USRD offers other standard hydrophone systems for measuring ambient noise.) The H91 system is designed to monitor strong, low-frequency acoustic fields. To maximize the output signal-to-noise ratio, the gain of the H91 preamplifier should be set as high as possible for each H91 application. Table 1 shows the SPL range appropriate for each preamplifier gain.

### *4.2.5 Receiver Design*

Figure 14 is a block diagram of the receiver. The receiver (1) interfaces with the "dry end" of the tow cable, (2) provides power to and demodulates the FM signal from the H91 hydrophone preamplifier, and (3) provides optional operator control of the preamplifier's gain. In figure 14, the tow cable enters at the left and the demodulated audio is output at the right.

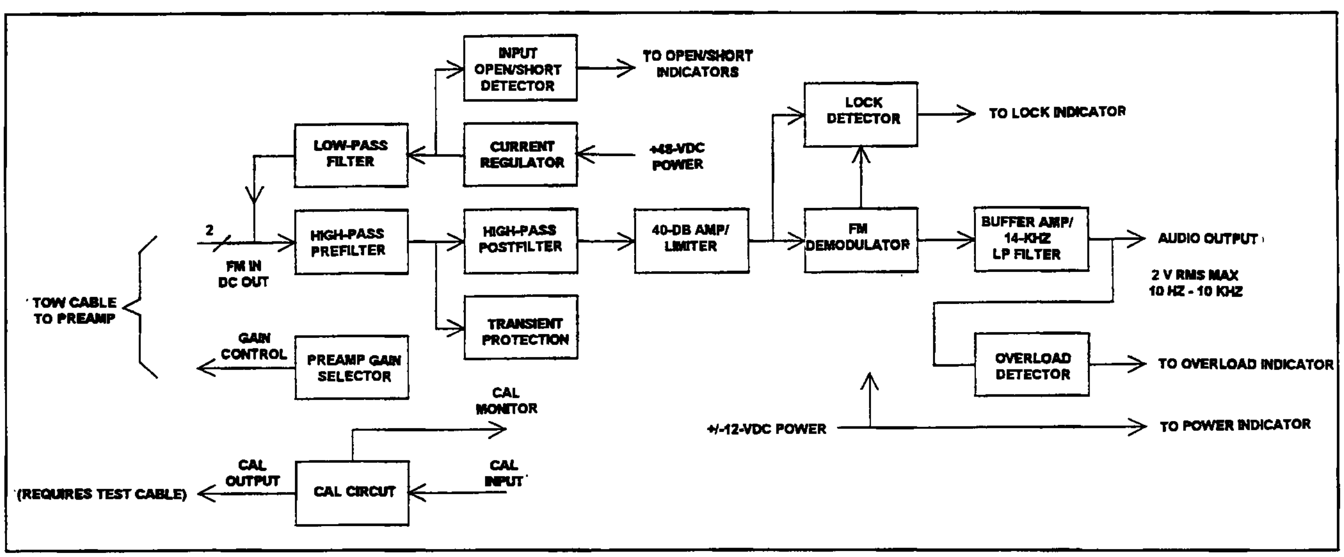


***Figure 14. H91 Receiver Block Diagram***

The incoming FM signal is about 1 Vrms for a short tow cable, but it could be at a much lower level if the cable is very long. As described in the previous section, the FM signal is a 200 kHz carrier deviated in frequency to a maximum of ±50 kHz. A full-scale deviation of ±50 kHz corresponds to an audio output of 2 Vrms.

The wire pair carrying the FM signal also carries a constant 30-mA supply current to the H91 preamplifier. Depending on the length of the tow cable, this constant supply current results in a dc level at the receiver input of +16 to +32 Vdc. A high-pass prefilter stage blocks the dc from the FM signal path. An opened or shorted FM wire pair condition is detected and indicated by front panel indicator lamps.

High levels of audio crosstalk may be coupled into the hydrophone wire pair in the tow cable as a result of a high-drive voltage for the projector on nearby conductors in the cable. The low-pass and high-pass filters at the receiver/cable interface are designed to significantly attenuate such crosstalk.

After being filtered, the FM signal passes through a 40-dB amplifier/limiter stage, which eliminates all amplitude variation by boosting and clipping. The resulting FM from the limiter is essentially a square wave at ±0.7 V peak-to-peak (pp) and is passed to the demodulator stage.

The demodulator extracts the original audio signal from the FM, i.e., the output of the hydrophone preamplifier prior to modulation. However, the demodulator output also contains strong carrier components, which are removed by a 4-pole, 14-kHz low-pass filter, providing a clean recovered audio signal. This stage also serves as an output buffer. An internal adjustment allows the full-scale output to be trimmed to 2 Vrms for a full-scale input deviation of ±50 kHz. Outputs exceeding 2 Vrms are detected, illuminating a front panel overload lamp.

A lock detector circuit compares the input to the demodulator stage with an internal quadrature signal in the demodulator. When these two signals are in phase, the demodulator is locked onto the FM carrier. This condition is displayed on the front panel lock indicator lamp.

All the circuitry described so far operates solely on the two-conductor hydrophone wire pair. If a third wire is available in the tow cable, the user can control the hydrophone preamplifier gain at the receiver with a simple three-position switch that places a dc level on the gain control wire.

A calibration circuit in the receiver allows a calibration signal to be sent to the H91 hydrophone, providing a nonacoustic means of testing the H91 system. The calibration circuit is normally used only by USRD personnel in the process of adjusting or repairing an H91 system. A special, short test cable with extra conductors for the calibration signal is required.

Nonacoustic calibration is not accurate when the H91 system is used with a long tow cable. Even when additional wires are available in the tow cable for the calibration signal, part of the signal is shunted by the capacitance of the long cable and does not reach the hydrophone preamplifier. However, for benchtop tests using a short test cable, the calibration circuit is accurate and useful.

## 4.3 CROSSTALK

Crosstalk is a significant problem when a projector drive signal and a hydrophone output signal share a common tow cable. This problem arises from the proximity of the hydrophone conductors to the projector drive wires in the tow cable and the high drive signal on the projector wires relative to the small hydrophone output. It is inevitable that in this situation part of the drive signal is impressed directly onto the hydrophone signal via unwanted coupling in the cable. Unwanted coupling causes a serious problem: crosstalk signals and normal hydrophone output signals cannot be distinguished because they are at the same frequency.

This section discusses the mechanism by which crosstalk in a tow cable occurs, describes laboratory measurements of crosstalk in a sample length of a typical tow cable, and shows how the H91 system is designed to overcome the crosstalk problem. Additional laboratory measurements, which demonstrate the H91 crosstalk rejection capability, are described.

### *4.3.1 Theory*

Figure 15 shows two lossless conductor pairs in proximity and is a simplified representation of the coupling that can exist in a typical tow cable.

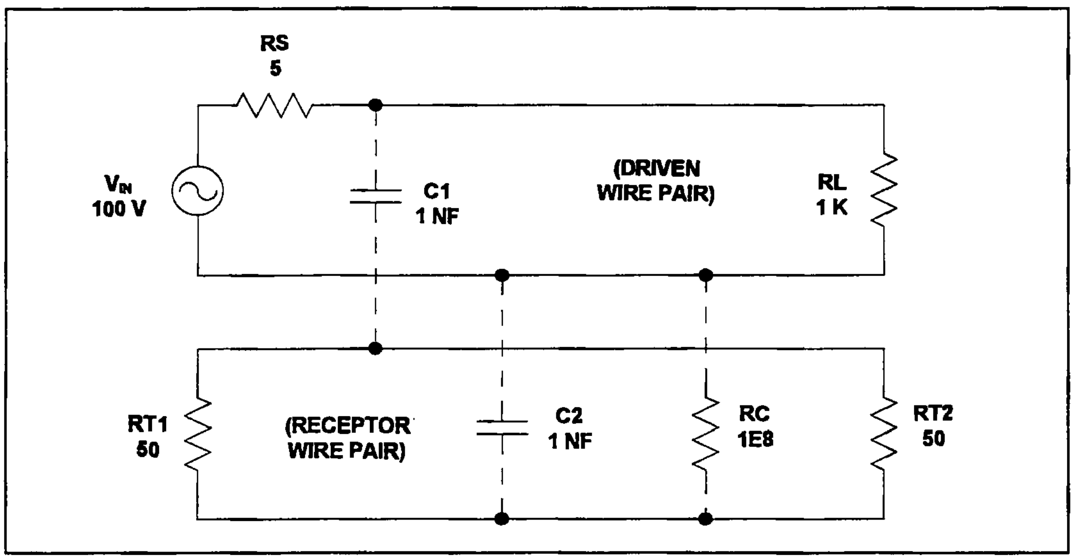


***Figure 15. Simple Coupling Between Two Pairs of Electrical Conductors***

In figure 15, $V_{IN}$ represents a strong signal using the top wire pair to drive load RL. RS represents the source impedance of $V_{IN}$. The bottom wire pair is connected to low-valued termination resistors, which, ideally, should receive none of the drive signal. However, because the wire pairs are long and close to each other, they are coupled by capacitances C1 and C2. Resistor RC represents insulation resistance between the low side of each wire pair. Although the component values in figure 15 are somewhat arbitrary, they approximate conditions observed in some tow cables. Figure 16 shows the voltage that is coupled to RT2 in the circuit shown in figure 15.

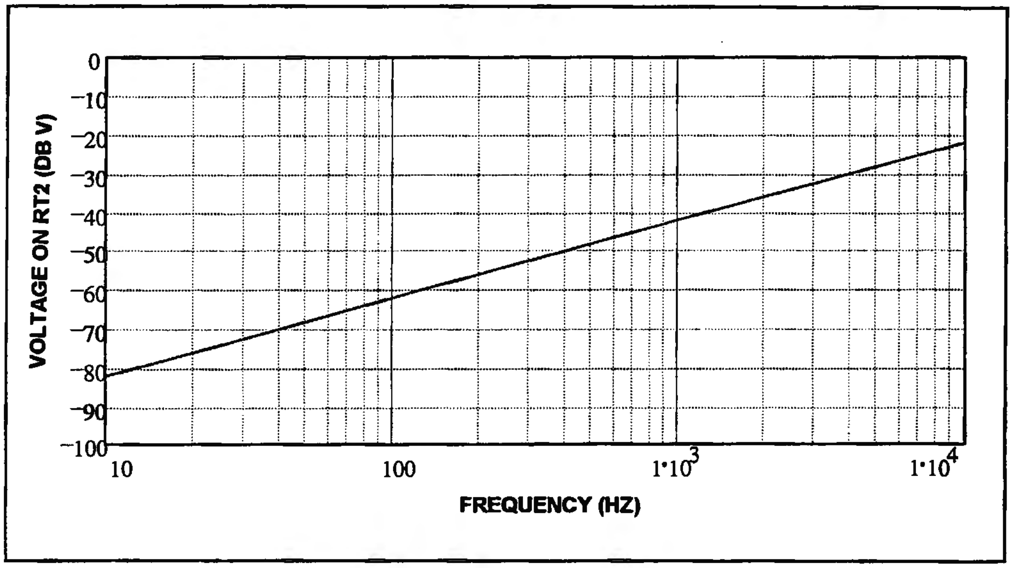


***Figure 16. Voltage Across RT2, in dB re 1 Vrms (dB V), for Circuit in Figure 15***

For this simple cable model, the voltage coupled to RT2 from the 100-V source is about -82 dB V at 10 Hz and -22 dB V at 10 kHz (80 μV and 80 mV, respectively). Plotted on a log scale, the coupled voltage is a straight line rising at 20 dB per decade of frequency.

A tow cable presents a more complex situation. Tow cables typically have both coaxial and noncoaxial conductors, and both are lossy; that is, the conductors have series resistance and inductance, as well as shunting capacitances, distributed over their length. Coupling between conductors may occur inductively as well as capacitively. Also, cable terminations may not be as simple as those in figure 15.

In practice, unwanted coupling increases with signal frequency. The coupled signal level depends on the level of the source ($V_{IN}$), the length and structure of the cable, the degree of shielding between conductors, cable losses, and external terminations.

### *4.3.2 Laboratory Measurements of Tow Cable Crosstalk, H91 Omitted*

A 1084-foot sample of type C0-05MOF cable was tested at the USRD to get an idea of the crosstalk levels that occur in tow cables at sea. The H91 system was omitted for these tests. (The tests were later repeated with the H91 system included, as described in paragraph 4.3.3.)

C0-05MOF cable contains an internal coaxial cable and four single conductors, all surrounded by an overall braided shield. The coaxial member has a No. 22 AWG inner conductor and a braided shield. Each single conductor is No. 20 AWG stranded. The four individual conductors are color-coded: red, green, white, and black (R, G, W, and B).

Two tests were conducted. For each test, a pair of unshielded conductors were driven at 100 Vrms. The first test measured crosstalk coupled into the coaxial cable member. The second test measured crosstalk coupled into a pair of unshielded conductors.

The C0-05MOF cable was uncoiled from its spool and stretched around the building for these crosstalk measurements. It was important to uncoil the cable for the tests because a coiled multiconductor cable has different conductor-to-conductor crosstalk from one that is laid straight. In a coiled cable, each cable loop is inductively coupled to adjacent loops; this condition does not exist with an uncoiled length of cable. Care was also taken not to wrap the cable back onto itself because doing so reduces crosstalk through inductive cancellation.

The first test (test 1A), shown in figure 17, measured crosstalk onto the coaxial member using the R-G pair of unshielded conductors for the drive signal. The R-G pair was terminated in 10 nF to represent a piezoelectric projector. The drive signal V1 was set to 100 Vrms. Each end of the coaxial cable was terminated in 50 ohms and coupled voltage V2 was sensed at one termination as shown. Frequency was swept from 100 Hz to 10 kHz while the ratio V2/V1 was measured and plotted in decibels. V1 was attenuated by 60 dB and V2 was boosted by 20 dB to accommodate the voltage limits of the analyzer. These factors were compensated for when the data were plotted.

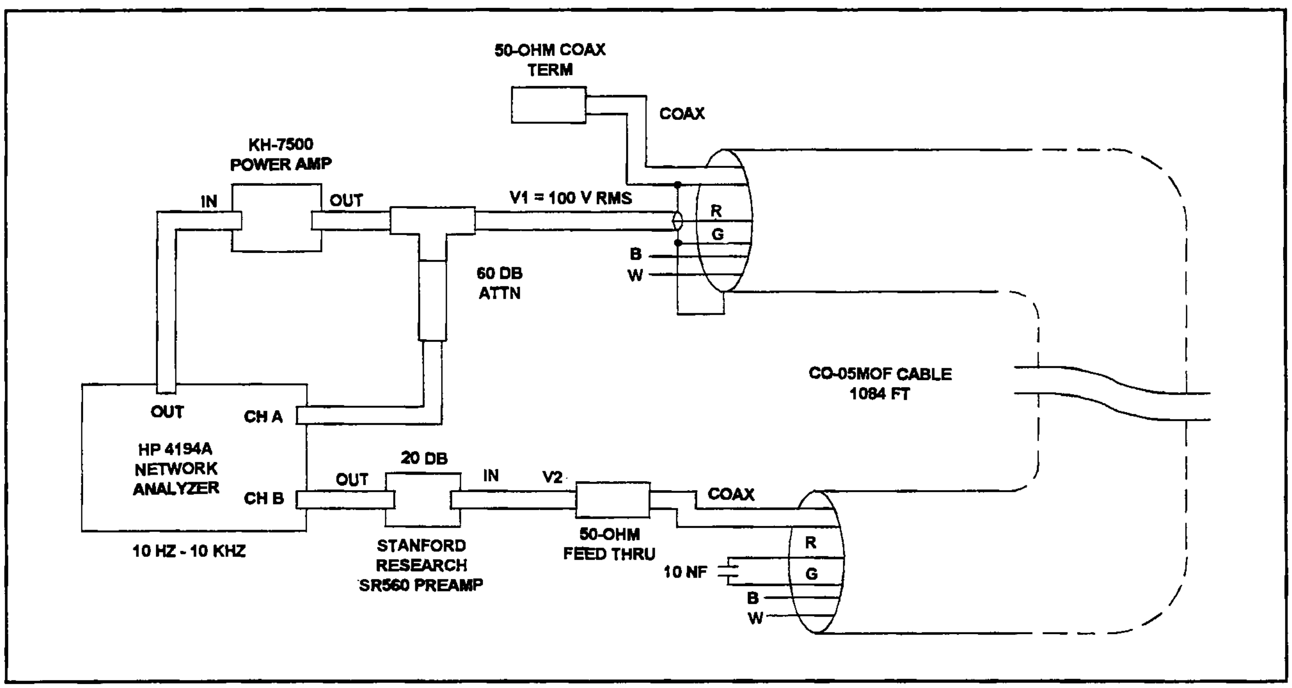


*Figure 17. Crosstalk Test 1A:*
*Driven Wire Pair Unshielded, Receptor Wire Pair Shielded, H91 Omitted*

The second test (test 2A), shown in figure 18, measured crosstalk using the R-G pair of unshielded conductors for the drive signal and the W-G pair of unshielded conductors for the received signal. The driven and receptor wire pairs were terminated in the same way as for the first test. The ratio V2/V1 was again measured and plotted in decibels over frequency. In this case, coupled voltage V2 was more than 6 dB higher than for the first test. Therefore, V2 was only boosted by 14 dB before input to the analyzer.

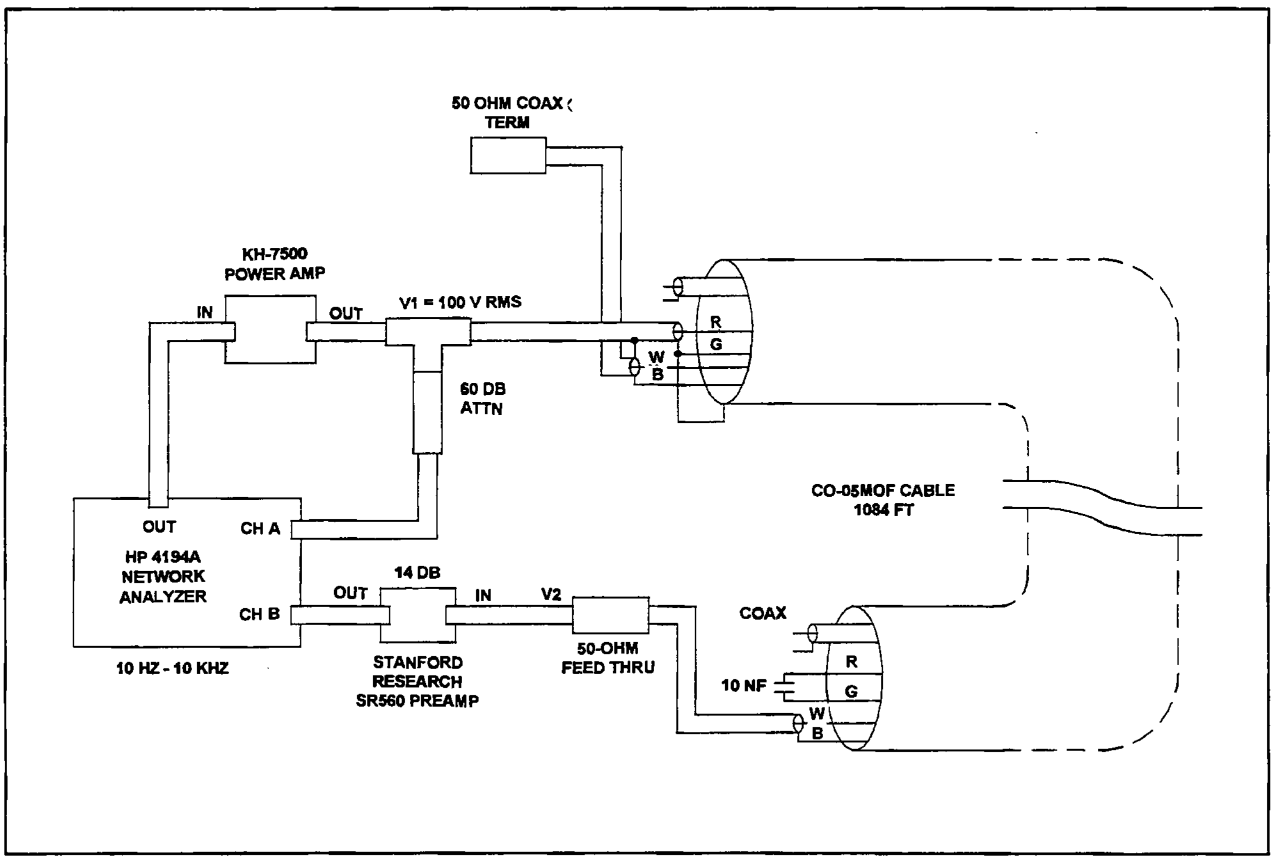


*Figure 18. Crosstalk Test 2A:*
*Driven Wire Pair Unshielded, Receptor Wire Pair Unshielded, H91 Omitted*

The results of these two tests are shown in figure 19. As expected, the crosstalk increased with frequency. However, the crosstalk levels measured in test 1A were lower than those of test 2A. This result is not surprising considering test 1A used shielded coaxial cable as the receptor wire pair, and test 2A used unshielded conductors.

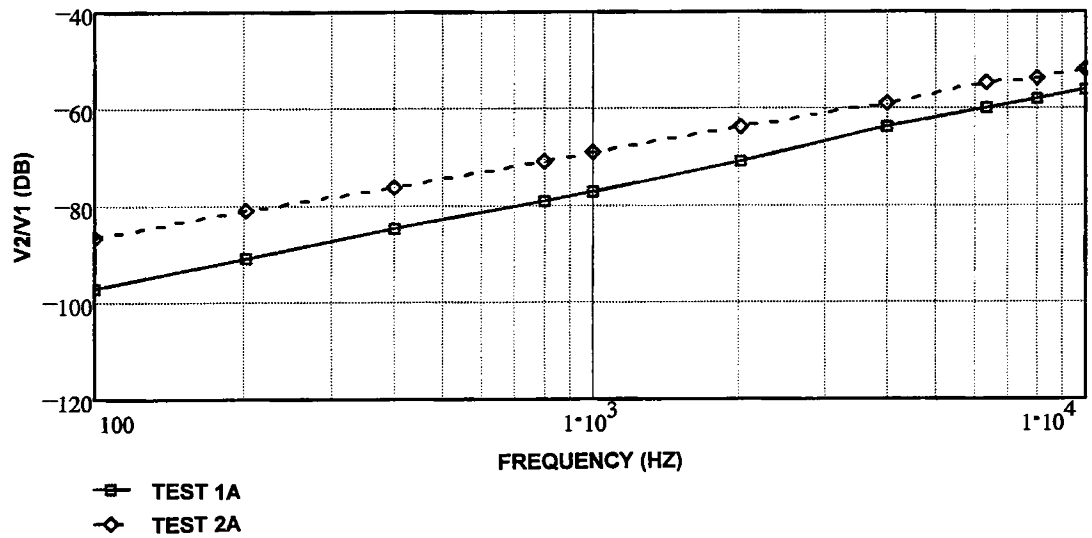


*Figure 19. Results of Crosstalk Tests 1A and 2A*

By using the information in figure 19, worst-case crosstalk levels for a 1084-foot C0-05MOF tow cable can be estimated as follows. Maximum crosstalk occurs at 10 kHz and is about -50 dB for an unshielded hydrophone wire pair and -56 dB for a shielded (coaxial) hydrophone wire pair. Projector drive voltage V1 can be as high as 1000 Vrms (60 dB V) in practice. Thus, one could expect 60 dB V - 50 dB, or 10 dB V, of unwanted 10 kHz audio coupled onto the unshielded wire pair. This amount is equivalent to 3.2 Vrms. Coupling onto the coaxial cable would be about 6 dB lower (1.6 Vrms).

A 20,000-foot tow cable would have roughly 18.5 times more capacitive coupling between the projector and hydrophone conductors and could add another 25 dB to the coupled voltage levels calculated for a 1084-foot tow cable. Therefore, up to 35 dB V (56 Vrms) of unwanted audio on an unshielded hydrophone wire pair in a 20,000-foot C0-05MOF tow cable could have been expected. If the hydrophone wire pair were shielded (coaxial), half as much coupled signal (28 Vrms) would have been expected.

This example shows why a conventional hydrophone will not work in this application. A hydrophone output signal, even with preamplification, is seldom more than a volt. Coupled audio from the projector conductors in a long tow cable can be more than 50 times greater, and the signals cannot be separated because they are at the same frequency.

### *4.3.3 Laboratory Measurements of Crosstalk Using H91 System*

The H91 system is designed to reject crosstalk in the tow cable through frequency modulation of the hydrophone signal. The information in the hydrophone signal is conveyed by the instantaneous frequency of the FM carrier. As long as this frequency can be reliably detected at the receiver, the original hydrophone signal can be recovered. The effect of crosstalk is to vary the amplitude of the FM carrier. As long as this amplitude variation does not affect the zero-crossings of the carrier, there is negligible change in the recovered output signal.

To preserve the zero-crossings of the FM carrier, the H91 receiver uses heavy filtering. This is required because, in a long cable, the carrier level can be in the millivolt range, while the coupled audio can be more than 50 V. The high-pass filters in the receiver are designed to reject the audio crosstalk but pass the FM signal. Similarly, a low-pass filter in the receiver rejects audio crosstalk and passes the dc supply current to the preamplifier. The filters are designed so that the receiver presents an impedance of 50 ohms to the hydrophone cable over the FM bandwidth.

The H91 hydrophone preamplifier is subject to the same crosstalk levels experienced by the receiver. Therefore, filters are included in the preamplifier cable interface to reject the crosstalk. The high- and low-pass filters in the preamplifier (figure 13) are analogous to those in the receiver and have the same purpose.

At the time of the crosstalk measurements (paragraph 4.3.2), the final electronics hardware for the H91D system had not been completed. A breadboard prototype was available, however. To assess the crosstalk rejection of the H91D system, the crosstalk tests described in paragraph 4.3.2 were repeated using the prototype breadboard. These new tests were labeled 1B and 2B, respectively, and are described in the following paragraphs.

Test 1B, shown in figure 20, was identical to test 1A except that the H91D receiver breadboard was included in test 1B. As in test 1A, drive signal V1 was set to 100 Vrms and frequency was swept from 100 Hz to 10 kHz. The coaxial cable member in the C0-05MOF sample was used for the H91 hydrophone wire pair. A frequency synthesizer, representing the hydrophone preamplifier, supplied a 1-Vrms, 200 kHz carrier signal to the coaxial cable. The H91D receiver, at the far end of the cable, received and demodulated this carrier signal. Because the carrier signal was not modulated, the H91D output, V2, should (ideally) have been zero. However, because the coaxial cable was subject to the same crosstalk as in test 1A, a small, but non-zero signal was detected at the receiver output. As in test 1A, V2/V1 was measured and plotted in decibels. The result of test 1B is compared with that of test 1A in figure 21. It can be seen that an improvement (i.e., reduction of crosstalk) of 55 to 60 dB was achieved by using the H91D system.

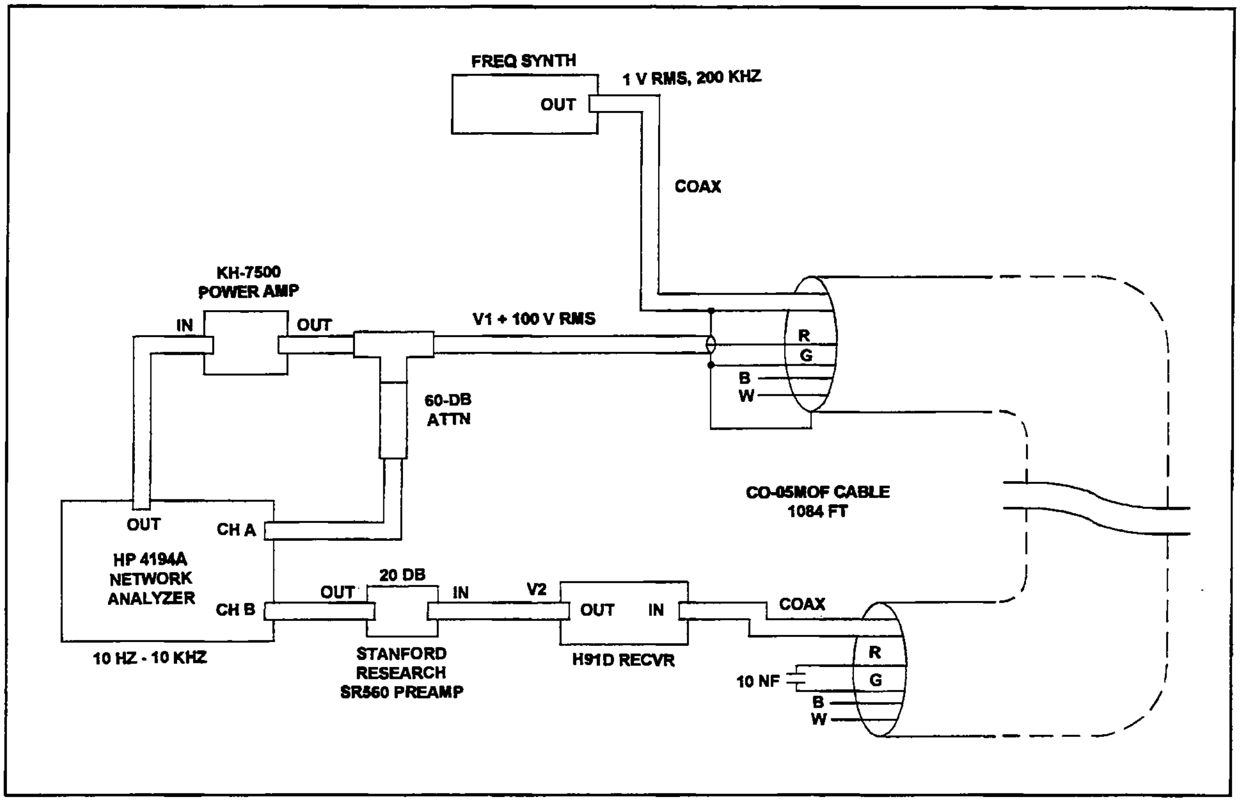


*Figure 20. Crosstalk Test 1B:*
*Driven Wire Pair Unshielded, Receptor Wire Pair Shielded, H91 Included*

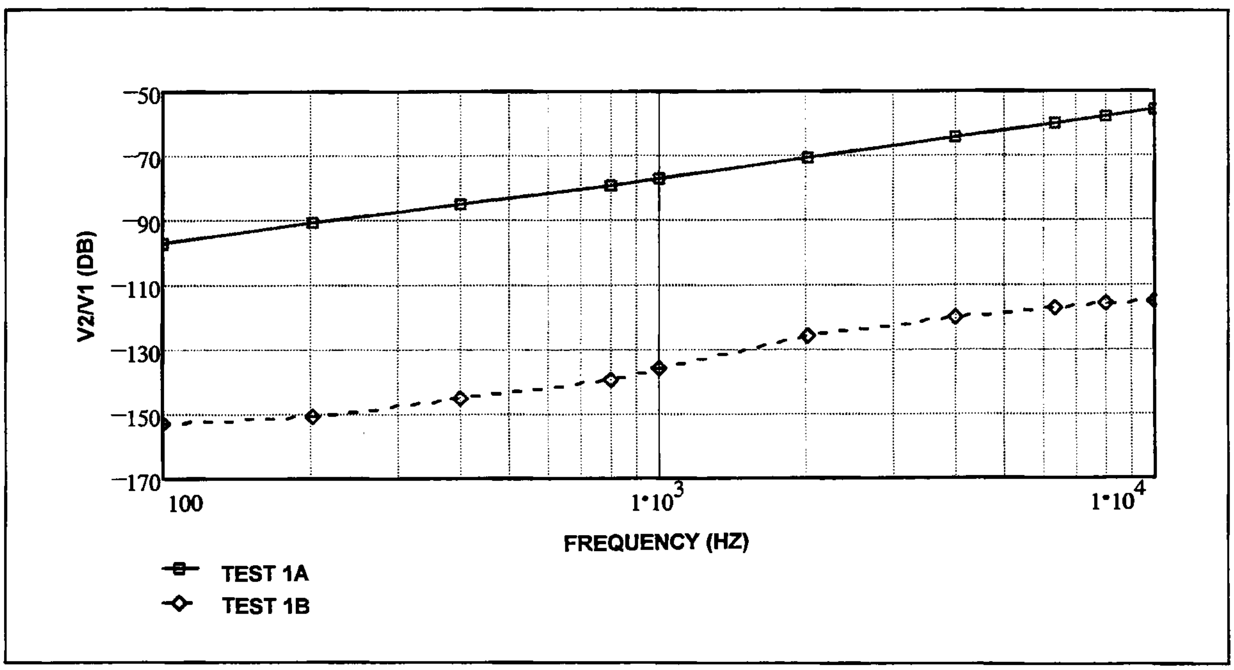


*Figure 21. Results of Cable Tests 1A and 1B:*
*Crosstalk Using Shielded Hydrophone Cable With (Bottom) and Without (Top) the H91 system*

Test 2B (figure 22) was identical to test 2A except that the H91D receiver breadboard was included in test 2B. In this case, the W-B unshielded conductors were used as the H91 hydrophone wire pair, over which the carrier signal was sent to the H91D receiver where it was demodulated. V2/V1 was again measured and plotted in decibels.

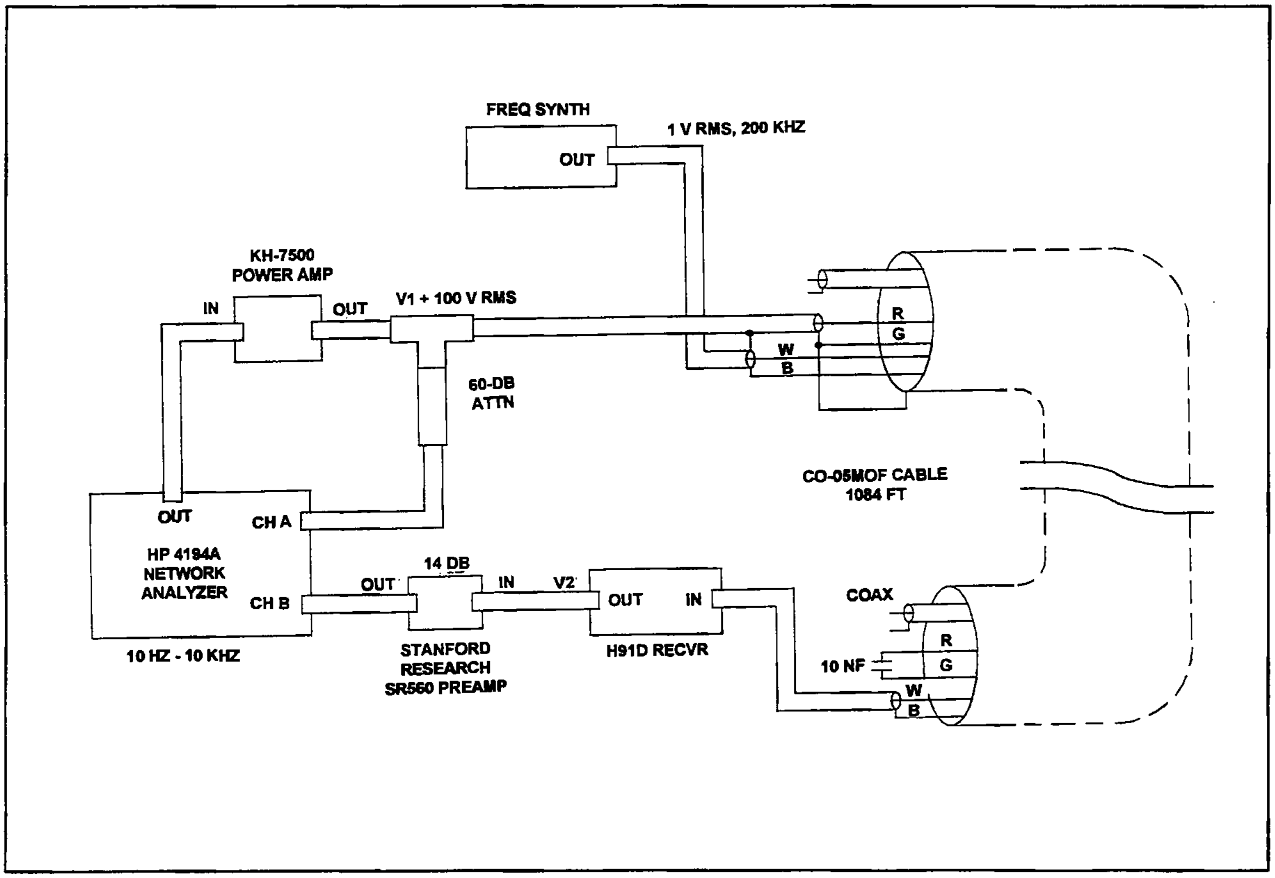


*Figure 22. Crosstalk Test 2B:*
*Driven Wire Pair Unshielded, Receptor Wire Pair Unshielded, H91 Included*

The result of test 2B is compared with that of test 2A in figure 23. A crosstalk reduction on the order of 60 dB was obtained by using the H91D system. In fact, the crosstalk levels of tests 1B and 2B (figures 21 and 23, respectively) are almost the same. The H91D system provided excellent crosstalk rejection in these laboratory tests.

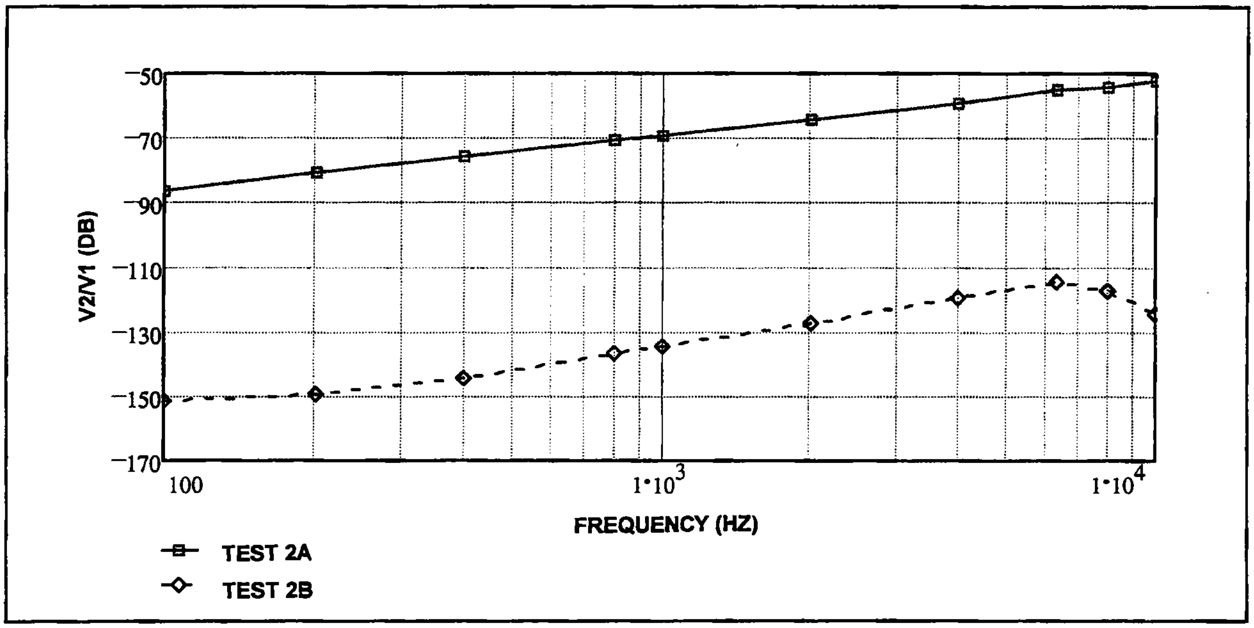


***Figure 23. Results of Cable Tests 2A and 2B: Crosstalk Using Unshielded Hydrophone Cable With (Bottom) and Without (Top) the H91 System***

The droop in the crosstalk curve above 6 kHz observed in test 2B (figure 23) was determined to be caused by a cable termination mismatch on the W-B wire pair. The impedance of the unshielded conductors in the C0-05MOF cable is uncontrolled and greatly different from the controlled impedance of the coaxial cable member. A cable mismatch was not observed when the coaxial cable was used for the carrier signal in test 1B.

## 4.4 GUIDELINES FOR OPTIMUM H91 SYSTEM PERFORMANCE

Because tow cables used with the H91 systems vary from user to user, crosstalk levels cannot be predicted for all situations. The projector drive signal will be coupled, to some degree, into the hydrophone cable in every application. The H91 system provides good crosstalk rejection. However, the user should observe the following guidelines to ensure optimum system performance.

- Use shielded cables, whenever possible, for both the projector and hydrophone conductors. Both twisted, shielded pairs and coaxial cables are good, and either type is preferred over nonshielded conductors. If only a single shielded cable is available in the tow cable, it should be used for the hydrophone signal. Avoid using unshielded wires in proximity to each other for both the projector and hydrophone signals.

- Ensure that the cable wiring restricts projector current to the projector wire pair only. The projector return current must never be allowed to flow on the hydrophone cable shield or "low" conductor, because direct coupling of audio to the hydrophone cable occurs and could damage the H91 receiver.

- Select a low-loss cable for the FM wire pair to minimize attenuation of the FM signal as it travels up the cable.

- Choose a 50-ohm cable (characteristic impedance) for the FM wire pair to match the receiver input impedance.

- Ensure that the total dc resistance of the FM wire pair does not exceed 500 ohms so that the receiver 30-mA current source operates properly.

- Do not use cables that are longer than necessary and do not use projector drive levels that are higher than necessary.

- Select the highest gain for the H91 preamplifier that will avoid overdriving the system. Refer to table 1 or the appendix to select a gain appropriate for the anticipated SPL range.

# 5. OPERATIONAL CHARACTERISTICS

## 5.1 SENSOR ORIENTATION

The H91 sensor is oriented as a sphere in the left-hand coordinate system defined in the *American Standard Procedures for Calibration of Electroacoustic Transducers*, Z24.24-1957. Refer to figure 4 and Groves.[14] The geometrical center of the sensor is at the origin of the coordinates with the longitudinal axis aligned with the Z-axis. The seams of the encapsulating mold are used as zero-reference marks for the X- and Y-axes during calibration.

## 5.2 DIRECTIVITY

The H91 transducer is omnidirectional in the XY- and XZ-planes up to a frequency of 100 kHz. Sensor construction uses few metal parts, which could interfere with the sound field. The characteristic impedance of the polyurethane encapsulating material closely matches that of water, ensuring acoustic transparency.

A sphere with radial polarization and displacement is theoretically omnidirectional in both the XY- and XZ-planes. In practice, the directivity pattern deviates from this ideal as the wavelength approaches the diameter of the sphere. This deviation is caused by imperfections such as inconsistent polarization between sphere walls, variations in wall thickness and hemisphere diameter, misalignment of the hemispheres, and proximity of the cable gland assembly.

## 5.3 CALIBRATION

To calibrate an H91 system, a sensor/preamplifier assembly is connected to a receiver through a 30-m test cable and attenuation network. The attenuation network simulates cable loss and resistance in a long tow cable.

It is recommended that the delivered sensor/preamplifier/receiver combination be used as a unit by the customer. While H91 parts are interchangeable, the system calibration is guaranteed for only the particular components tested.

## 5.4 FFVS AND PREAMPLIFIER GAIN

Figure 12 shows the H91 FFVS for the three standard preamplifier gains. Table 1 shows the appropriate gains to use for various SPL ranges to avoid overdriving the system. The highest appropriate preamplifier gain should be chosen for a given application. If the user's requirements include an SPL range requiring more than one gain setting, then a third conductor should be made available in the tow cable for gain control.

## 6. SUMMARY

This report has described the theory, construction, and operation of the H91 Monitor Hydrophone System for low-frequency towed projectors. The H91 system covers a 10-Hz to 10-kHz bandwidth and operates over a spare wire pair in the same tow cable that drives the projector. The system design was discussed in terms of its crosstalk rejection capability. Crosstalk rejection is achieved by filtering and frequency modulation for the hydrophone signal.

Crosstalk measurements made for a 1084-foot sample tow cable were described. Crosstalk in the cable alone was first measured as a baseline. The tests were then repeated with the H91 system connected. Crosstalk reduction of up to 60 dB was obtained using the H91 system in these tests.

Finally, guidelines were given for hydrophone cable selection and connections. The cable is a crucial part of the H91 Monitor Hydrophone System and affects overall system performance. By adhering to the guidelines provided in this report, optimal system performance can be obtained.

Earlier versions of the H91 system have been used successfully by U. S. Navy activities and contractors for more than 10 years. The current version in development, H91D, uses a more integrated electronics package for greater reliability and ease of maintenance.

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## APPENDIX

## SYSTEM SPECIFICATIONS

The specifications given below are for the latest version (H91D) of the H91 system. If the system is to be operated at fixed gain, the user should ensure that the anticipated SPL range is within the limits shown for the specific gain chosen. Other customized gains are available.

Please note that the H91 system is designed for monitoring reasonably strong sound fields. The system is not intended for ambient noise measurements or other applications where signal levels are extremely low. Please contact the USRD if a noise-measuring hydrophone system is required.

| | | |
|---|---|---|
| H91 System Components: | (1) Sensor Assembly<br>(2) Preamplifier Assembly<br>(3) Receiver | |
| Sensor Sensitivity: | -201 dB, nominal, re 1 V/μPa | |
| Hydrophone Preamplifier Gain: | 20, 0, or -20 dB - selectable | |
| SPL Range for Preamplifier Gain of: | 20 dB | 127 - 187 dB re 1 μPa |
| | 0 dB | 167 - 207 dB re 1 μPa |
| | -20 dB | 187 - 227 dB re 1 μPa |
| Bandwidth: | 10 Hz - 10 kHz | |
| Preamplifier Supply Current: | 30-mA dc, nominal, from receiver on FM wire pair | |
| FM Carrier: | 1-Vrms, 200-kHz triangle wave into 50 ohms<br>±50-kHz deviation for full-scale output | |
| Receiver Input Impedance: | 50 ohm nominal over FM bandwidth<br>300 ohm maximum, 10 Hz - 10 kHz | |
| Receiver Output, Full Scale: | 2 Vrms (6-dB V) for ±50-kHz input modulation | |
| Receiver Output Noise: | -120-dB V/$\sqrt{\text{Hz}}$ (maximum)<br>100 Hz - 10 kHz for zero-input modulation | |
| Receiver Power Requirement: | 120 Vrms, 60 Hz, 250 mA | |
| Crosstalk Rejection: | 30 dB (minimum) | |

| | |
|---|---|
| Directivity Pattern: | Omnidirectional |
| Tow Velocity: | 15 knots (maximum) |
| Hydrostatic Pressure: | 470 psi (maximum) |
| Operational Temperature: | 0 to 30°C |
| Tow Cable Requirement: | |
| Conductors: | FM Signal - two wires (50-ohm coaxial recommended)<br>Remote Gain Selection - one additional wire |
| dc Resistance: | 500 ohms (maximum), FM and gain control conductors (high conductor plus return conductor) |
| Attenuation of FM wire pair: | 30 dB (maximum) @ 300 kHz |

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